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G. Colombo[2] and P. Higbie[3]

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Summary.--An accurate determination of the instantaneous orientation of the Explorer XI Satellite (γ-ray telescope) was very important for the analysis of the data from the main experiment. Many precise observations of the solar transit obtained by means of sun and earth aspect sensors were recorded by the MIT Cosmic-Ray Group. On some days more than 60 observations of the phase angle were recorded with an accuracy of 0.1 sec, which corresponds to a few degrees' accuracy in the orientation of the satellite axis. In particular, this observational material is useful for studying the short-periodic variation of the angular velocity.

An analysis of the decay of the average daily angular velocity in the 200-day period of observations will be given first. This decay is most likely due to eddy-current and magnetic hysteresis torques. However, a distinct correlation between variations in these (estimated by computing the daily average of $H_\perp^2$) and the measured damping torque is not completely clear. Any such correlation would be modulated by changes in the electrical and magnetic properties of the satellite components caused by variations in temperature.

In the second part an analysis of the angular velocity fluctuation with a period of one orbital revolution will be made. The oscillation is explained by the variation of the body's moment of inertia by thermal expansion and contraction because of periodic changes in the satellite's temperature caused by the passage of the satellite through the earth's shadow.

author

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1. The satellite is an elongated body and is shown in figure 1. Fifteen days after launch the motion about the center of mass became a rotational motion around the axis of maximum moment of inertia (a transversal axis) with a period slowly increasing from 12.34 sec to 15.85 sec in 180 days (from the 20th to the 200th after launch).

The axis of rotation, which was almost fixed in the body, moved in space with a slow precessional motion (a few degrees per day on the average) (fig. 2). The precessional motion of the tumbling axis was caused by the differential gravity torque and, mainly, by the torque experienced by the earth's magnetic field on the equivalent magnetic dipole of the satellite (Colombo, 1962; Naumann, 1961). This torque amounts to a few hundred dyne-cm.

The decaying of the magnitude of the angular momentum, that is, the decay of the tumbling angular velocity, is believed to be due mainly to the damping torque (of the order of 1 dyne-cm in average) caused by the eddy currents and by the magnetic hysteresis effect. The maximum daily average of this damping torque is less than 2 dyne-cm. The daily average angular velocity and deceleration plotted against time (fig. 3) after firing definitely shows a characteristic behavior, which at the first analysis was believed to be correlated only with the variation of the square of the component $H_{\perp}$ of the magnetic field $\vec{H}$ normal to the axis of rotation (see Colombo, 1962). The correlation is not very clear in the second period (120 to 200 days after launch).

In figure 3 we have plotted against time the average angular velocity and the average angular deceleration, the daily average value of the square of the component $H_{\perp}$ of the earth's magnetic field, the measured temperature of the MIT package and of the battery, the daily geomagnetic index, and the average fraction per day of the orbital period (108 minutes) the satellite spent in sunlight. All these variables affect in some manner the conductivity and the magnetic permeability of the satellite as well as the earth's magnetic field, and consequently affect the damping torque. It seems very difficult to derive a definite quantitative conclusion on the behavior of the angular velocity decay, mostly because this angular deceleration is an accumulation of different effects. In the next sections an analysis will be made of the variation with time of the average daily torque.

2. Let us assume the equation of motion around the tumbling axis to be of the type

$$\frac{d}{dt}(I\omega) = -(\alpha\omega + \beta) H_{\perp}^{2} . \qquad (1)$$

Here I is the moment of inertia of the body about the tumbling axis, ω the instanteous angular velocity, $\alpha\omega H_\perp^2$ the eddy-current torque, and $\beta H_\perp^2$ the magnetic hysteresis torque.

We may write equation (1) in the following form:

$$I \frac{d\omega}{dt} = - (\alpha\omega + \beta) H_\perp^2 - \omega \frac{dI}{dt} \quad . \tag{2}$$

The term $\omega \frac{dI}{dt}$ would take into account the possible changing of the moment of inertia with time. The latter may be due to a) thermal expansion b) displacement of masses inside the body, and c) second-order effects of the main gravitational and magnetic torques that caused the precessional motion of the tumbling axis. A fairly good representation of the angular velocity variation with time for the period of observation is given by

$$\frac{d\omega}{dt} = \exp\left[-7.3 \times 10^{-3}\ t\right] (-20.7 + 16.2 \cos \sigma t) , \qquad (t \geq 35) \quad , \tag{3}$$

where t is in days after launch day, $\frac{d\omega}{dt}$ in rev/day^2, and $\sigma = \frac{2\pi}{55}$ day^{-1}.

This acceleration may be considered as the sum of an exponential decay term with a relaxation time of 137 days plus a damped oscillation of the acceleration with the same relaxation time, and with an initial amplitude of the same order of magnitude of the initial value of $\frac{d\omega}{dt}$. The period of the damped oscillation is almost equal to the period of the precessional motion of the tumbling axis described in Colombo (1962). This was the reason why we first thought of a correlation between the variation of the orientation of the tumbling axis with respect to the earth's magnetic field, which causes variation of the average value of $H_\perp^2$, and the variation of the angular acceleration. We shall now examine various mechanisms to see which might explain the periodic component of the deceleration (3).

First suppose the term $\omega \frac{dI}{dt}$ in (2) to be negligible, which means the term $- (\alpha\omega + \beta) H_\perp^2$ is responsible for the fluctuations of $\frac{d\omega}{dt}$. Since the amplitude of the periodic variation of $H_\perp^2$ is not more than

10 per cent of the average value, if α and β are almost constant, we may have to suppose that $H_\perp^2$ has to overcome a threshold value in order to make the eddy-current and hysteresis torques effective for damping the angular velocity. This threshold value could be related to the actual existence of a fairly strong permanent magnetization of the body. If the external field is not strong enough the eddy-current torque could not occur. For these reasons the actual dependence of the eddy-current torque on $H_\perp^2$, for a body with an intrinsic dipole and with ferromagnetic parts, is perhaps far from being a directly proportional dependence. This may be just our case, since we know from the observed precessional motion of the tumbling axis that the component along the tumbling axis of the satellite's equivalent dipole was of the order of 0.6 amp - m^2. Experimentation is greatly needed on the eddy-current and magnetic hysteresis torques in a magnetized conductor. The parameter α is directly proportional to the conductivity σ of the components of the payload and to the square of the permeability μ; the parameter β is also proportional to μ^2. The conductivity σ definitely increases as the temperature decreases; the permeability μ of a metal also changes with the temperature, but the change varies strongly from metal to metal and according to the range of temperature variation. For a very low field, such as the earth's magnetic field, and for iron and some alloys, μ increases with increasing temperature in the actual range of temperature variation (-100° to $+100^\circ$) (Denker, 1962; Metals Handbook, 1961).

In figure 3 we have plotted the measured temperatures of the MIT package and of the Marshall package against time (Lumpkin, 1962). A correlation between the measured temperature of the MIT package and the deceleration in the first period of the observations can be seen. An evaluation of the changing with time of the coefficients α and β would be very difficult for many reasons the most important one is that no experimental observations are available of the changing with temperature of the permeability for a very weak field. The correlation between temperature and deceleration could lead to the conclusion that the decrease in μ with decreasing temperature is more important than the increase of σ with the decreasing T, since the torque decreases as T decreases.

Combining the variation of $H_\perp^2$ along the path of the satellite and the variation of σ and μ with time could explain the damping of the torque, but any evaluation of σ and μ would be based on very poorly known physical properties of the payloads components. The position of perigee with respect to the sun can be very important if we consider the short periodic temperature variations of the skin of the satellite as it passes from sunlight to shadow.

Concerning the change in $H_\perp^2$ (see fig. 3), we also plotted the geomagnetic index for reasons of completeness since the fluctuations of the earth's magnetic field with time are never greater than a few per cent of the average value. On the other hand, we have observed a few coincidences between sudden variations in the acceleration with sudden variations in the geomagnetic index (56, 63, 196 days after firing).[4]

We try now to evaluate $\omega \frac{dI}{dt}$ in terms of the magnitude of the corresponding torque. Since ω is of the order of 0.5 rad/sec, $\frac{dI}{dt}$ has to be of the order of 1 gram-cm^2/sec for $\omega \frac{dI}{dt}$ to be comparable with the oscillating torque. In 27 days the moment of inertia, I, should have changed by 1.727×10^6 gram-cm^2. This variation corresponds to a 1-cm displacement of 0.8 kg at a distance of 1 meter from the axis, which seems very improbable. On the other hand, since the moment of inertia of the satellite is 1.6×10^8 gram-cm^2, a variation of 1.728×10^6 gram-cm^2 in 27 days corresponds to an expansion and contraction of 0.5 per cent; this means that the variation in the average temperature would be many hundreds of degrees centigrade, which is not very likely. In fact, we may assume from observations that the average temperature of the main parts of the body will not vary more than 50°C in 27 days.

Let us call I(t) the average moment of inertia in a one-day period, $I_T(t)$ a hypothetical oscillation component of I(t) which is responsible for the periodic oscillation, $\omega_T(t)$, of ω with a period of 55 days. Hence we may write, neglecting second-order terms,

$$\frac{dI_T}{dt} = - \frac{I}{\omega} \frac{d\omega_T}{dt} = - \frac{1.6 \times 10^8}{6300 \times 2\pi} 16.2 \times 2\pi \cos \sigma t \text{ gram-cm}^2 - \text{day}^{-1} ,$$

and we find that

$$I_T = - 3.6 \times 10^6 \sin \sigma t \text{ gram-cm}^2 .$$

[4] Variations in the geomagnetic index are known to be correlated with variations in the atmospheric density. The normal atmospheric drag torque, however, is so small as to be negligible in the damping process.

So I_T has an amplitude of 2.2 per cent of the moment of inertia, which correspond to a temperature range of 600° if we assume that the mean thermal coefficient of expansion is $1.5 \times 10^{-5}\ ^{\circ}C^{-1}$.

Finally, we shall rule out the possibility that the oscillating term in the deceleration is a second-order effect of the torques (gravitational and magnetic) producing the precessional motion of the tumbling axis. Our main arguments are first, that this should have exactly the same period as the precessional motion, and second, that there is no evident reason why this oscillatory term has to decay in amplitude. On the other hand, the displacement of the tumbling axis per day is less than 10°, which corresponds to an angular velocity of less than 10^{-5} rad/sec. Since the angular velocity of the satellite is of the order of 0.5 rad/sec, the direction of the actual axis of rotation of the rigid body (obtained by the sum of the tumbling angular velocity vector and the angular velocity of precession vector) does not differ from the direction of the axis of tumbling by more than 2×10^{-5} rad. This rules out the possibility that a residual of an initial Poinsot precessional motion (which was damped out by the nutation damper) can explain the change in angular velocity with the change of the actual axis of rotation. For a Poinsot motion (constant energy, constant angular momentum), if we call A, B, I the principal moments of inertia ($I > B > A$), and p, q, r the components of the angular velocity with respect to the principal axis of the body, we will have

$$I \frac{dr}{dt} = (A - B)\, p q \quad ,$$

and, since in the present case $I \cong B \gg A$,

$$\frac{dr}{dt} \cong p\, q \quad .$$

Because $p^2 + q^2 < 10^{-10}\ \mathrm{sec}^{-2}$, we have $|pq| < 0.7 \times 10^{-10}\ \mathrm{sec}^{-2}$, which means that $\frac{dr}{dt}$ is two orders of magnitude less than the observed oscillation of $\frac{d\omega}{dt}$, which is more than $1.3 \times 10^{-8}\ \mathrm{sec}^{-2}$.

3. We consider in this section the short period effect in the phase shift detected from the many observations taken in the 4 days, May 13, Aug. 17, Oct. 1, Oct. 12. Figure 4 shows the difference $\Delta\theta = N_o - N_c$ between the number of revolutions observed at any event time and the number of revolutions computed for the same instant on the hypothesis that the damping torque is constant during the day; the value of the average torque (i.e., the value of the average deceleration) is obtained from the least-squares method, using all the observations of the day. In figure 5 we have plotted $\Delta\theta$ superimposing on the interval, corresponding to the first orbital period, all the intervals corresponding to the following orbital periods of the day. The maximum observed shift in any orbital period of the phase varies from about -0.04 to about 0.04 revolutions. An increase in $\Delta\theta$ after the exit of the satellite from the earth's shadow and a decrease near the end of the time the satellite spent in sunlight is more or less well defined for each day; in any case it is always evident. It is interesting to note here that Lockwood (1960) has observed an acceleration in the spin rate of the Satellite Echo I as it started to pass into the earth's shadow; this was certainly due to the same thermal effects.

We will explain this phase-shift behavior as a consequence of the thermal expansion and contraction of the satellite. Let us call $\Delta\theta T(t)$ the variation of $\theta(t)$ due to the variation of the temperature T of the satellite. Naturally, since in one day the portion of the orbit with respect to the earth's shadow does not change, the function $\theta T(t)$ can be considered as a periodic function, with the period equal to the orbital period.

In figure 6 the measured temperatures of the 4th-stage motor case for those days closest to the days of many observations are plotted, and in figure 7 the temperatures of a sensor thermally isolated from the satellite but exposed to the sun. (Snoddy, 1961; Lumpkin, 1962).

Since the expansion and contraction of the skin of the satellite is most probably responsible for the change in the moment of inertia with temperature, a fairly good approximation based on these measurements is a temperature variation as plotted in figure 9. As we are working with phase observations having an accuracy better than 0.008 rev (which corresponds to an accuracy in time measurement of 0.1 sec), we think we are justified in assuming that the temperature behavior plotted in figure 9 is a reasonable approximation of the temperatures observed on any day, irrespective of the day. Hence T is assumed to decrease linearly from T_1 to T_0 in the first third of the period, to increase linearly from T_0 to T_1 in the second third of the period, and finally to be constant for the remaining part of the orbital period. In the same figure 9 a more realistic behavior of the temperature variation is shown by a dotted line.

Let us rewrite equation (2) in the form

$$I \frac{d\omega}{dt} = - \omega \frac{dI}{dt} + \tau_m , \tag{4}$$

where τ_m is the damping magnetic torque. If we call ω_0 the average angular velocity for one day and neglect second-order terms, we may write

$$I \frac{d\omega}{dt} = - \omega_0 \frac{dI}{dt} + \tau_m . \tag{5}$$

Indeed,

$$I(t) = I_0 (1 - \alpha(t)) , \tag{6}$$

where $\alpha(t)$ is, as we shall see later, of the order of 10^{-3}, and ω does not change in one day more than $5 \times 10^{-3}\ \omega_0$. In equation (6), I_0 is the maximum moment of inertia, that is, the value of I at the maximum of the body's temperature.

By integrating (5) and neglecting small terms we have

$$\omega(t) = - \frac{\omega_0}{I_0} [I(t) - \tilde{I}] + \int_0^t \frac{1}{I} \tau_m \, dt , \tag{7}$$

where

$$\tilde{I} = \frac{1}{P} \int_0^P \tau_m(t) \, dt , \tag{8}$$

and

$$\omega_0 = \omega(0) \frac{I_0}{\tilde{I} - I_0} .$$

The first term on the right-hand side of eq. (7) is the periodic part of the angular velocity. We may now write the moment of inertia of the body as

$$I(t) = \alpha\, m\, \ell^2\, [T(t)] \quad , \tag{9}$$

where $\ell(T) = \ell_0\, [1 - \delta\, (T_1 - T)]$, $\ell_0 \cong 2.255$ m, m = 42.801 kg, and α is a number very close to 0.07 (a little less than for a homogeneous cylinder with the same length and the same mass). Let us call δ the average thermal expansion coefficient. Hence we may write

$$I(t) = \alpha\, m\, \ell_0^2\, [1 - 2\delta\, (T_1 - T)] \ . \tag{10}$$

If we call ω_T the angular velocity variation due the temperature fluctuation, we have

$$\omega_T = \frac{d\theta_T}{dt} = 2\, \omega_0\, \delta \left\{T_1 - T - \frac{1}{3}(T_1 - T_0)\right\} = \gamma\, f\,(t) \ , \tag{11}$$

where $\gamma = 2\, \omega_0\, \delta$ and

$$\left.\begin{aligned} f\,(t) &= (T_1 - T_0)\,\frac{3t}{P} - \frac{1}{3}(T_1 - T_0) \ , & 0 \le t \le \frac{P}{3}\ ; \\ f\,(t) &= \frac{3}{P}(T_1 - T_0)\left(\frac{2}{3}P - t\right) - \frac{1}{3}(T_1 - T_0), & \frac{P}{3} \le t \le \frac{2P}{3}\ ; \\ f\,(t) &= -\frac{1}{3}(T_1 - T_0) \ , & \frac{2P}{3} \le t \le P \ . \end{aligned}\right\} \tag{12}$$

By integration of (11) with the initial condition

$$\theta_T\,(0) = 0 \ , \tag{13}$$

We have

$$\left.\begin{aligned}
\theta_T(t) &= \frac{3\gamma}{2P}(T_1 - T_0)t^2 - \frac{\gamma}{3} t (T_1 - T_0) , && 0 \le t \le \frac{1}{3} P; \\
\theta_T(t) &= - \frac{3\gamma}{2P}(T_1 - T_0)\left(\frac{2P}{3} - t\right)^2 - \frac{\gamma}{3} t (T_1 - T_0) + \frac{\gamma}{3} P (T_1 - T_0), && \frac{P}{3} \le t \le \frac{2P}{3}; \\
\theta_T(t) &= - \frac{\gamma}{3P}(T_1 - T_0)t + \frac{\gamma}{3}(T_1 - T_0) , && \frac{2P}{3} \le t \le P ;
\end{aligned}\right\} \quad (14)$$

and

$$\left.\begin{aligned}
\theta_T\left(\frac{P}{3}\right) &= \frac{\gamma}{18} P (T_1 - T_0) , \\
\theta_T\left(\frac{2P}{3}\right) &= \frac{\gamma}{9} P (T_1 - T_0) , \\
\theta_T(0) &= \theta_T(P) = 0 .
\end{aligned}\right\} \quad (15)$$

The behavior of the function $\theta(T)$ is clearly represented in figure 9. The maximum phase shift is

$$\theta_T^{max} - \theta_T^{min} = \frac{8}{27} \omega_0 P \delta (T_1 - T_0) . \quad (16)$$

The maximum phase shift during the sunlight period is

$$\widetilde{\Delta\theta}_T = \frac{7}{27} \omega_0 P \delta (T_1 - T_0) . \quad (17)$$

If we assume $\delta = 1.4 \times 10^{-5}\ {}^{\circ}C^{-1}$, $\omega_0 = 6300$ rev/day, $T_1 - T_0 = 50^{\circ}$, $P = 108.2$ min $= 0.075$ day, we have

$$\widetilde{\Delta}\theta_T = 0.086 \text{ rev} . \tag{18}$$

The value chosen for δ is an average value of the thermal expansion coefficients of the different metals used for the main parts of the satellite; for instance, for the stainless steel of the 4th-stage motor case it is $1.3 \times 10^{-5}\ {}^{\circ}C^{-1}$; for the magnesium which was used in the MIT package it is $2 \times 10^{-5}\ {}^{\circ}C^{-1}$. Furthermore, if thermal gradients exist in the satellite, δ will also depend on the orientation of the tumble plane with respect to the sun. We have also assumed an average value for ω_0, since ω varies from 6700 to 5800 rev/day in the period of observations. Finally for the variations in temperature we based our assumptions on the temperature measurements of the 4th-stage motor case (see fig. 6) rather than on that of the isolated sensor, since we assume that the variation of the moment of inertia is mostly related to the expansion of the skin of the satellite, and since the alluminum disc of the isolated sensor (fig. 7) had a solar absorptivity-to-infrared emissivity ratio which caused the temperature of the disc to run higher.

Since the accuracy of the phase observations is better than 0.008 rev, a displacement in phase of 0.086 rev, as given by (18), should be detectable. In fact, as we said above, this is what appears clearly in figures 4 and 5. A tendency of gain in phase in the period just after exit from the earth's shadow is present, and more evident is a tendency of loss in phase toward the end of the sunlight period. A comparative analysis of the results for different days is quite difficult, since the effective temperature fluctuations for each day are not very well known although the range is close to 50°. The only datum we have is the time the satellite spent in sunlight (fig. 8) and, since this varies slightly for each day, it could be correlated with the amplitude of $T_1 - T_0$. In any event we do not think it is worthwhile to push further the analysis, since the agreement between theory and observation seems to be sufficiently good.

Short periodic variations in the drag torque, with a period of the order of one day and of the order of one orbital revolution, can be present, but simple estimates show they are not detectable because of poor statistics during one period and because of the superposition of so many different effects when comparing different days. The periodic term we have observed and explained is a very important one. The corresponding periodic torque, that is, the torque that can give the same effect, is easily computed.

We may write

$$\theta = 0.25 \sin\left(\frac{2\pi t}{6400}\right) \text{ rad, where } t \text{ is in seconds.}$$

Hence

$$\frac{d\omega}{dt} = - 0.25 \; \frac{4\pi^2 \times 10^{-6}}{(6.4)^2} \; \sin \left(\frac{2\pi t}{6400}\right) ,$$

and the torque is

$$\tau = I \frac{d\omega}{dt} = 39 \sin \left(\frac{2\pi t}{6400}\right) \text{ dyne-cm} \quad ,$$

which is much more important than the other damping torques. This observation enables us to say definitely that the observed phase shift is due to temperature variations.

Acknowledgment

We would like to thank Dr. Mercedes Agogino and Mr. Nicole Simon for preparing programs for the analysis, and the SAO and MIT Computation Centers for time on their computers.

We also thank Dr. Charles A. Lundquist for his careful reading of this paper and for his helpful comments.

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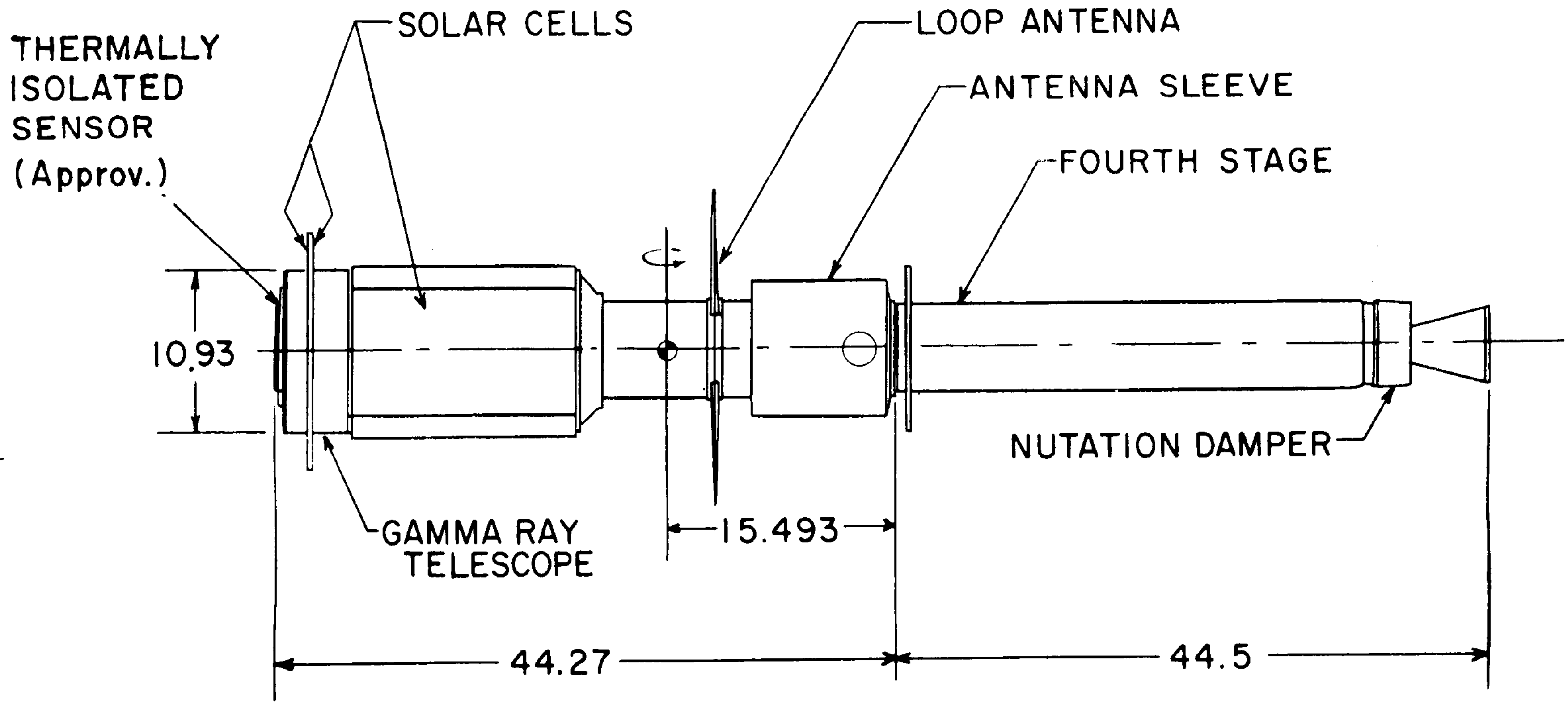

Figure 1.--Schematic drawing of Explorer XI. The total weight is 95.114 lbs. The moments of inertia are: A_{max} = 143.792 in. lb. sec^2; A_{min} = 143.601 in. lb. sec^2; and C = 3.405 in. lb. sec^2.

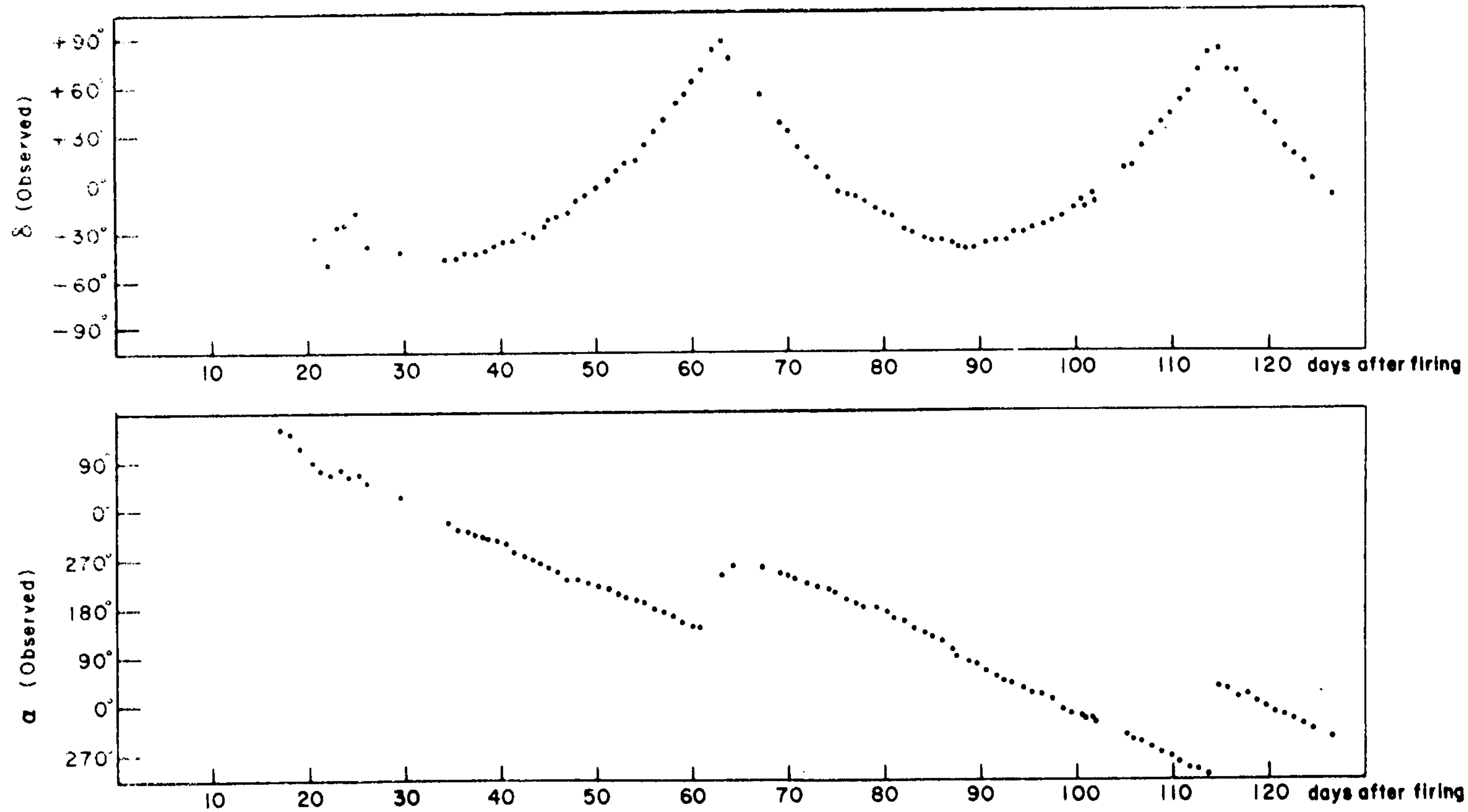

Figure 2.--Right ascension α and declination δ of the angular momentum axis versus time.

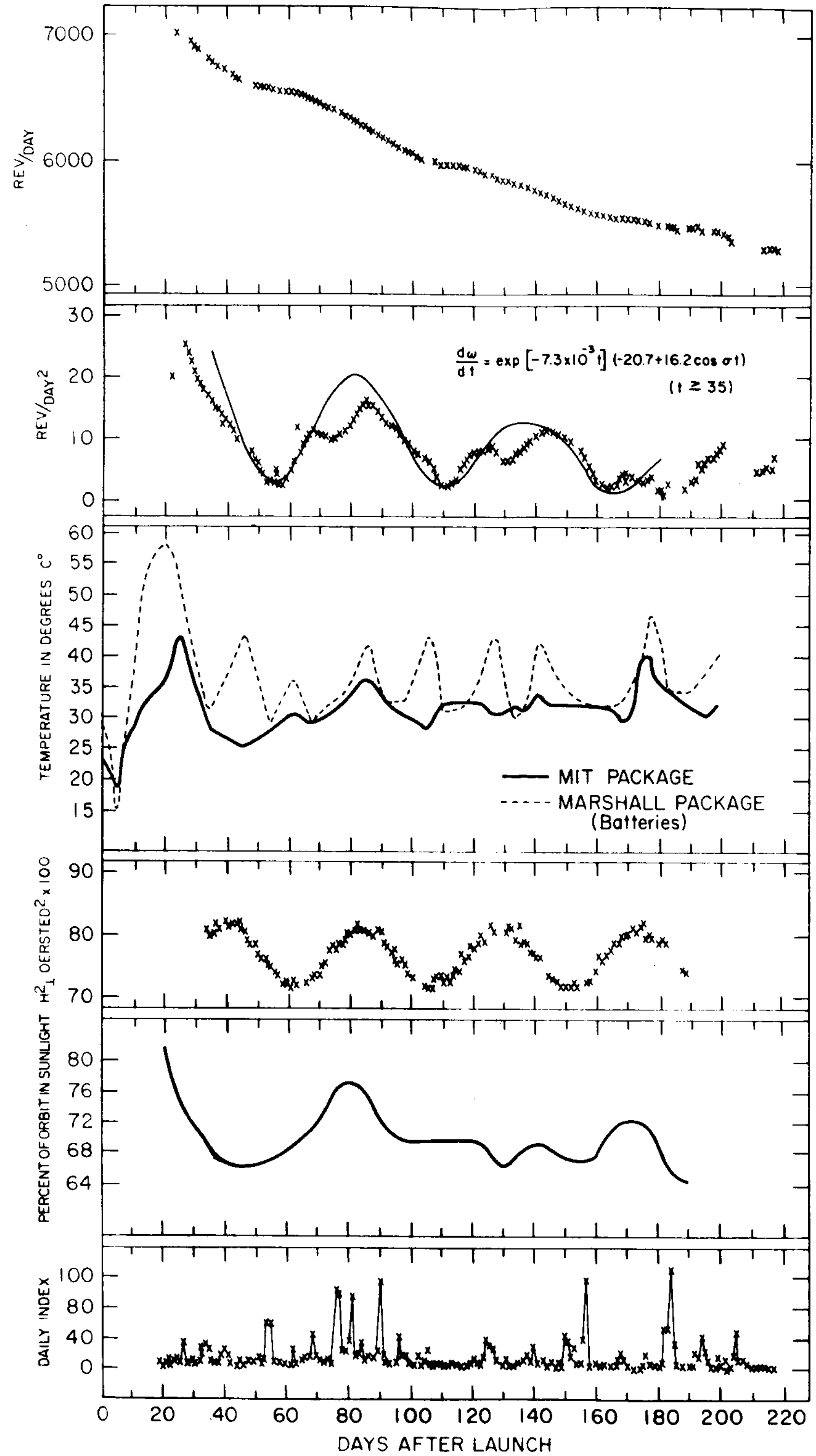

Figure 3, (a) and (b).--Constant and linear terms from least-squares fit to instantaneous tumble frequency; (c) temperature measurements by on-board sensors; (d) computed value of H_1^2 average over one day; (e) calculated per cent of orbit spent in sunlight; (f) daily geomagnetic index.

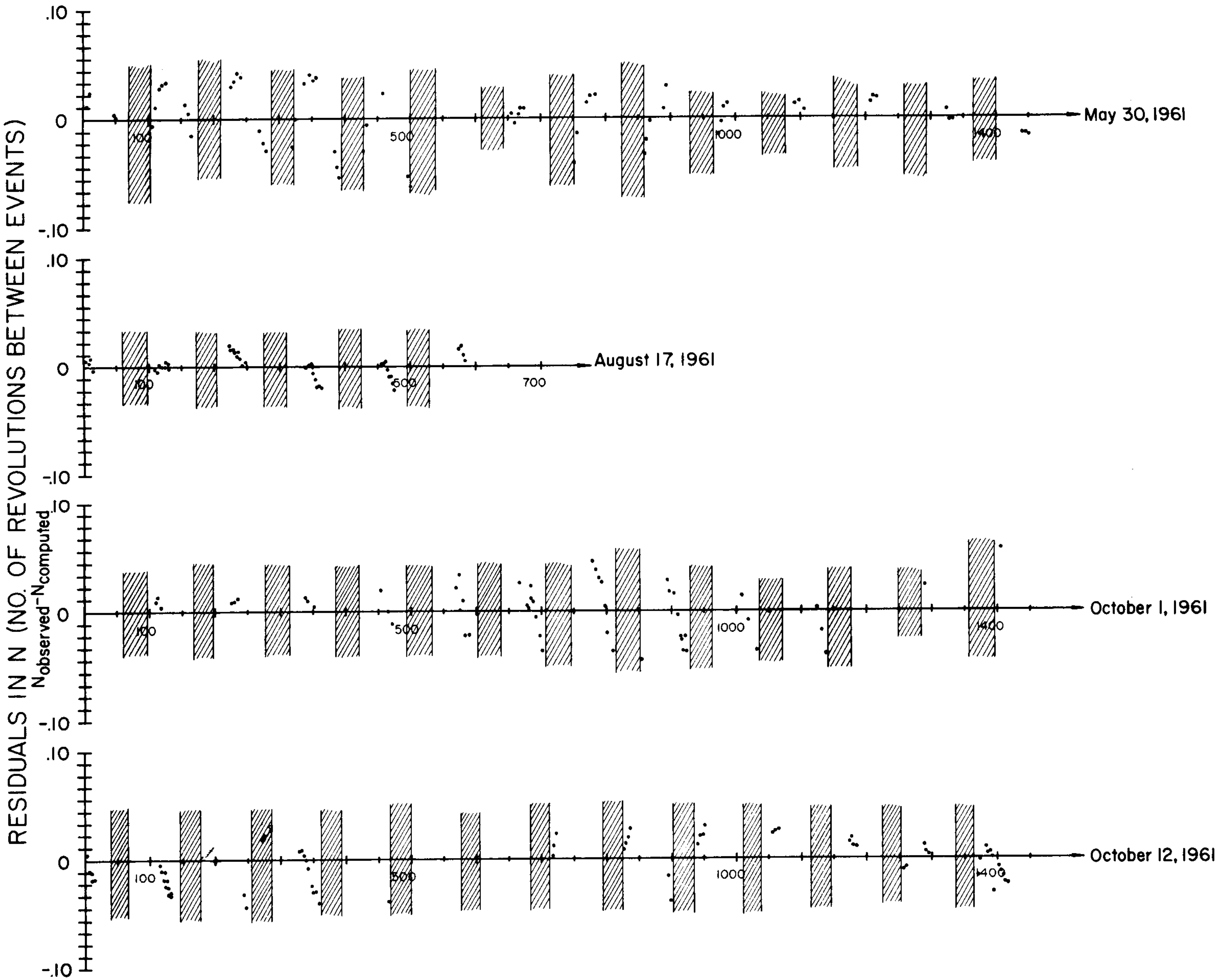

Figure 4.--Phase differences between observed and predicted sun transits during one day for the four days when many observations were made. Shaded areas indicate time satellite was in shadow.

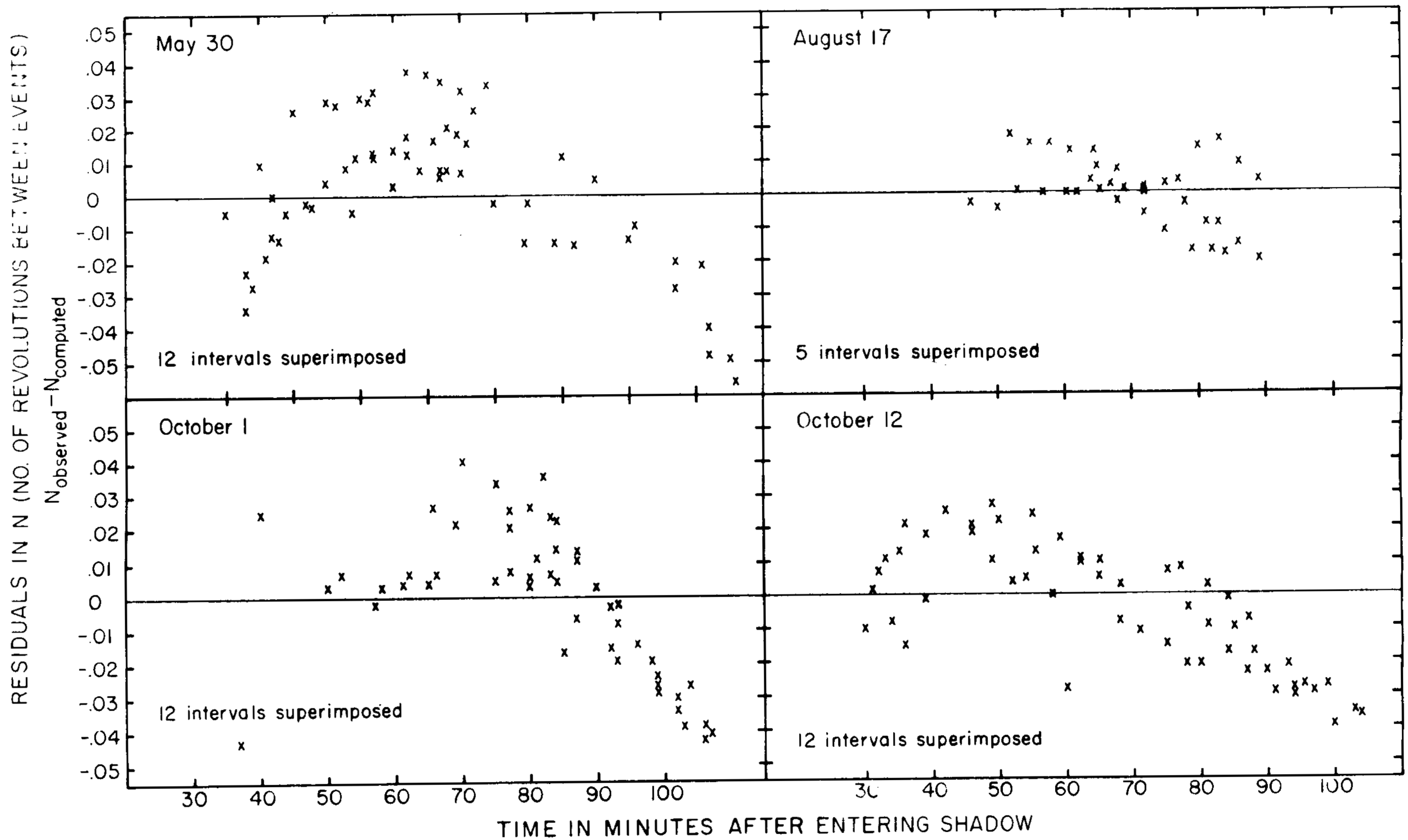

Figure 5.--Phase differences, illustrated in Figure 4, plotted modulo the orbital period of the satellite.

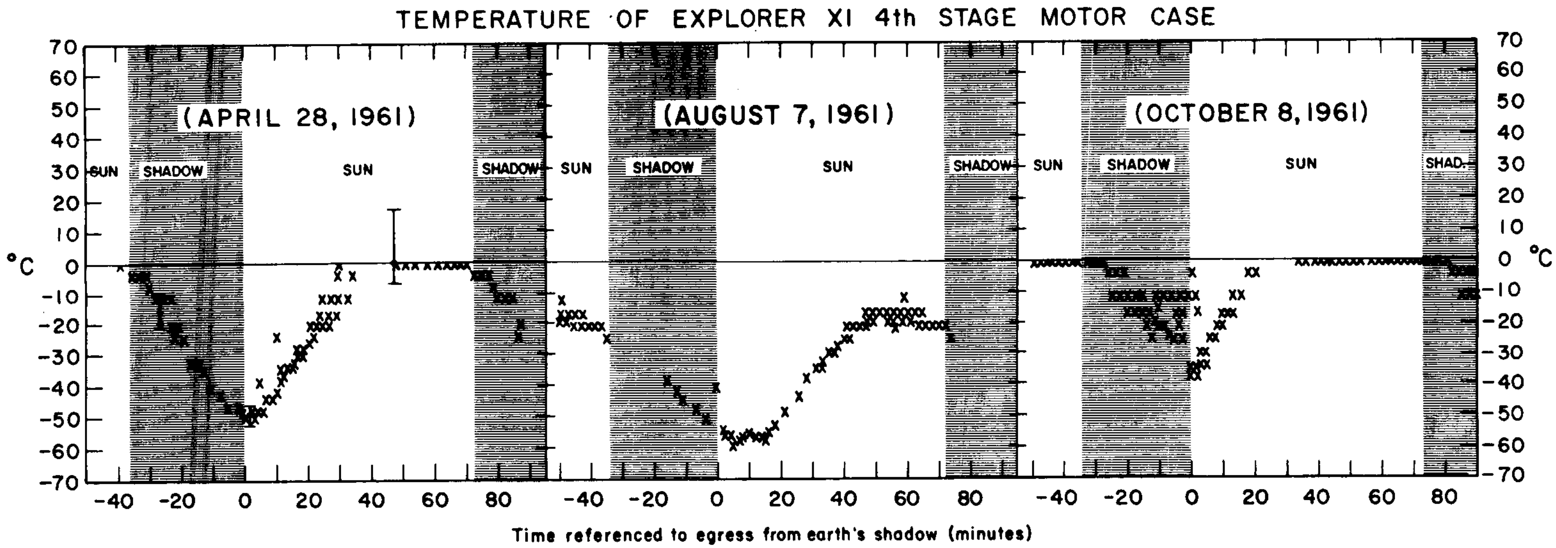

Figure 6.--Temperature of the 4th-stage motor case for representative days near those days for which phase-angle variations were measured.

TEMPERATURE OF THERMALLY ISOLATED SENSOR

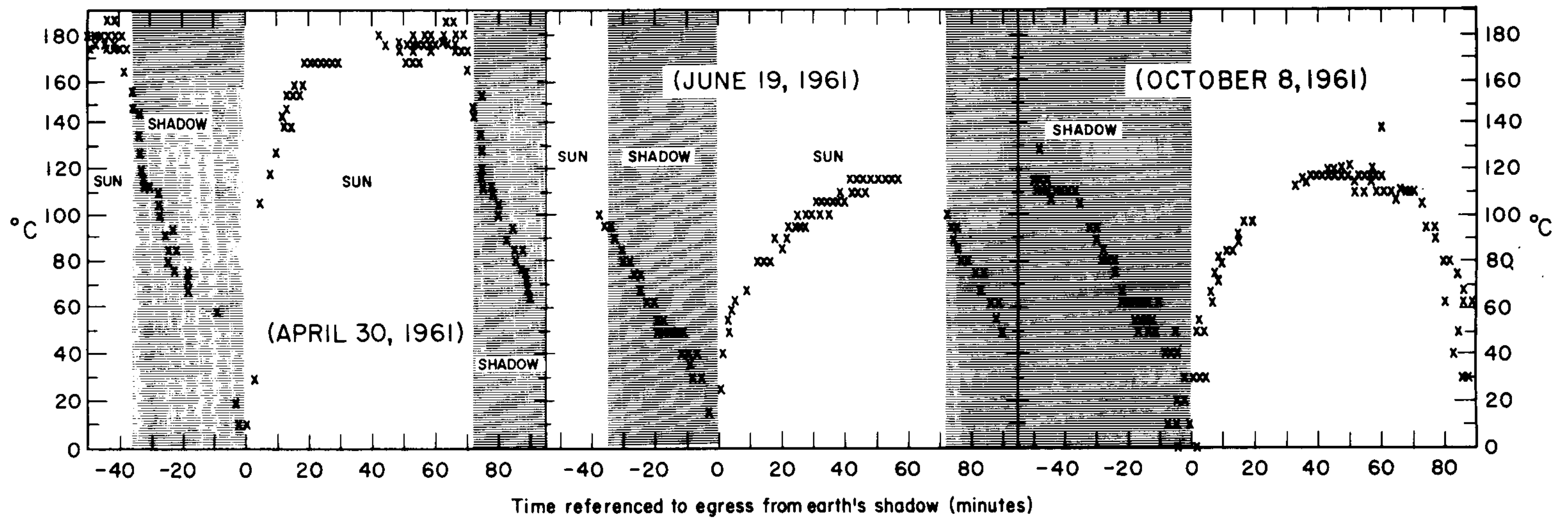

Figure 7.--Temperature of thermally isolated sensor.

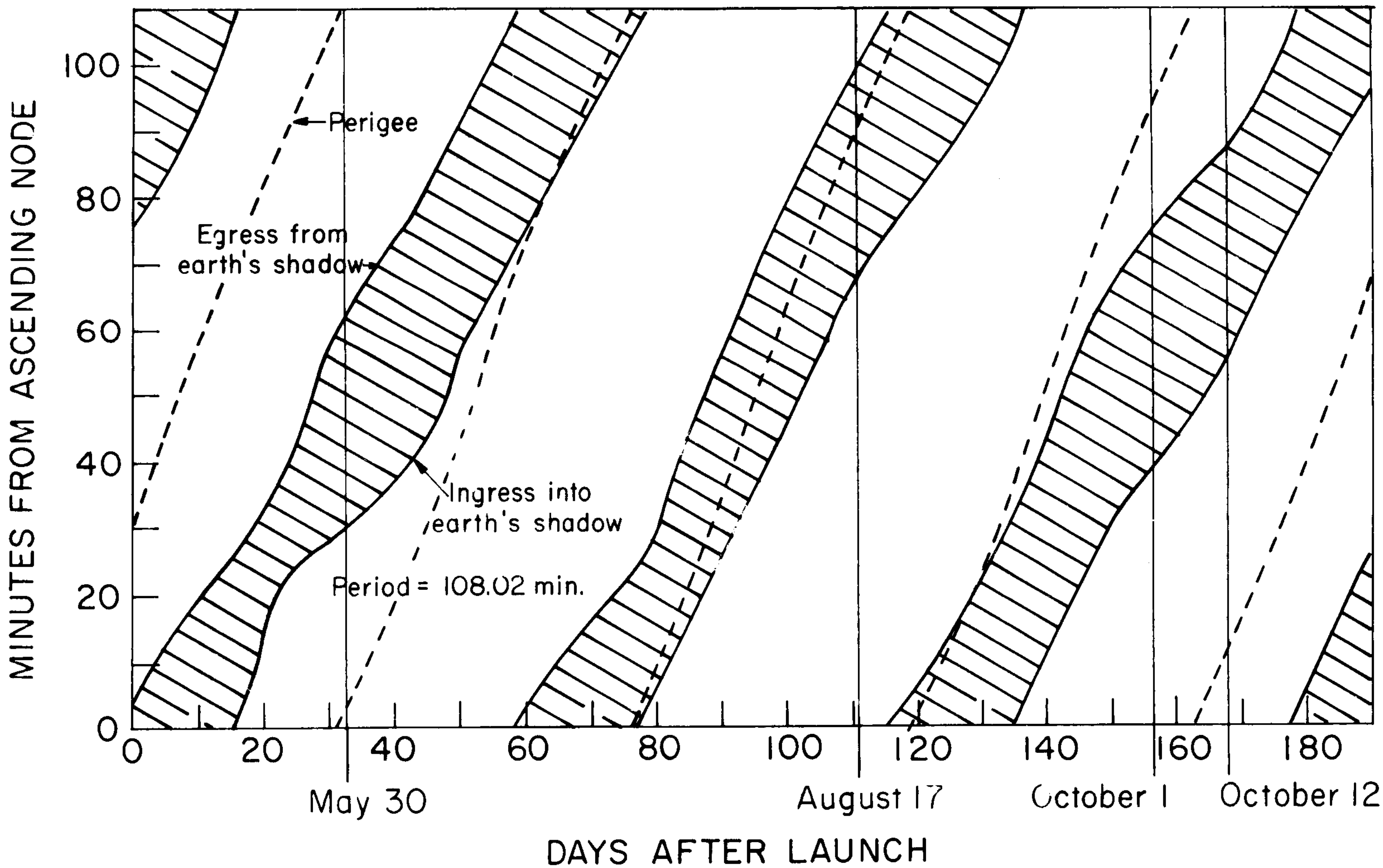

Figure 8.--Position of earth's shadow relative to orbit of satellite.

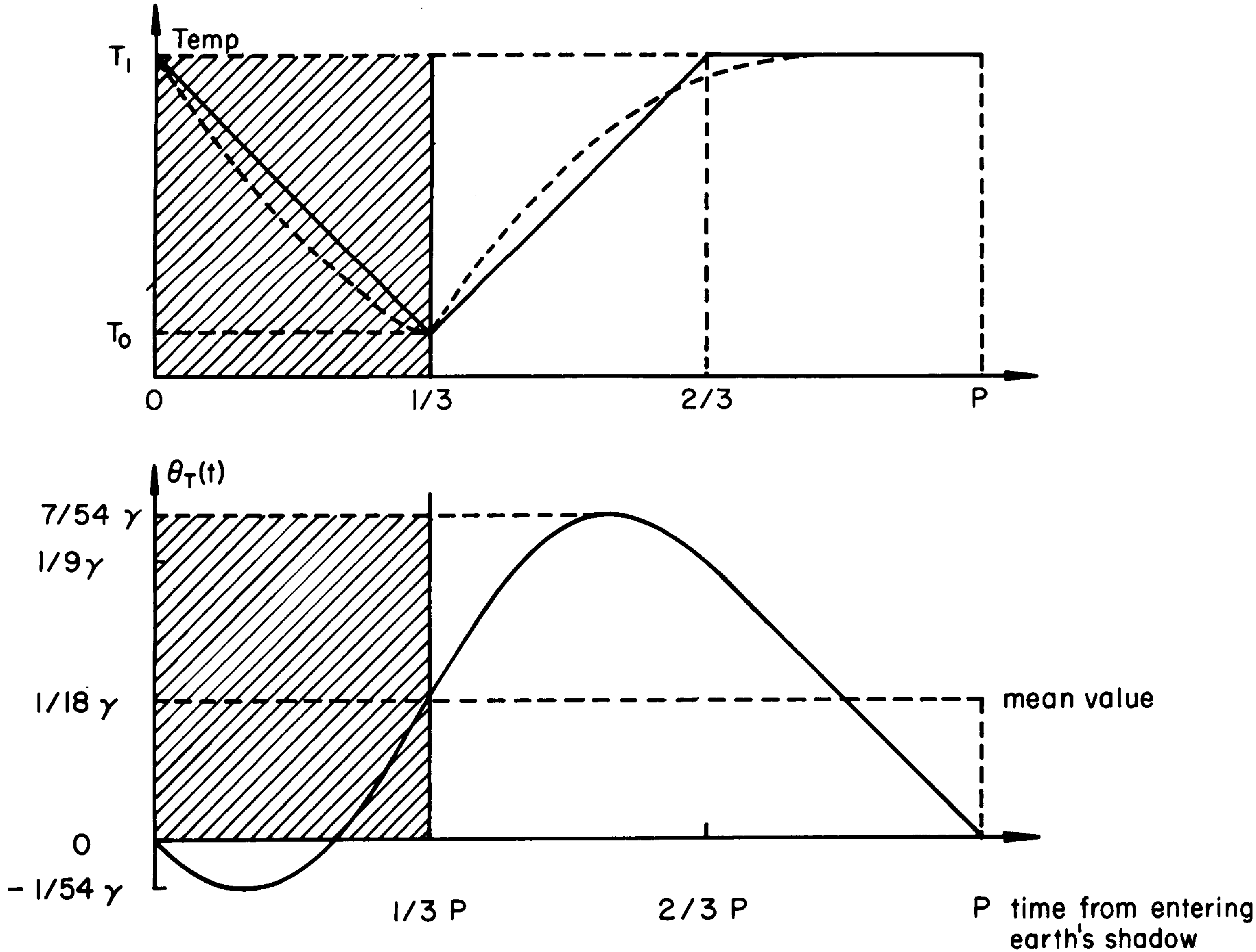

Figure 9, (a).--Assumed functional dependence of effective temperature. Dotted line suggests a more realistic function. P is the orbital period. (b) Component of phase angle of satellite in its rotation plane due to assumed temperature function; γ is explained in the text.

NOTICE

This series of Special Reports was instituted under the supervision of Dr. F. L. Whipple, Director of the Astrophysical Observatory of the Smithsonian Institution, shortly after the launching of the first artificial earth satellite on October 4, 1957. Contributions come from the Staff of the Observatory. First issued to ensure the immediate dissemination of data for satellite tracking, the Reports have continued to provide a rapid distribution of catalogues of satellite observations, orbital information, and preliminary results of data analyses prior to formal publication in the appropriate journals.

Edited and produced under the supervision of Mr. E. N. Hayes and Mrs. Barbara J. Mello, the reports are indexed by the Science and Technology Division of the Library of Congress, and are regularly distributed to all institutions participating in the U. S. space research program and to individual scientists who request them from the Administrative Officer, Technical Information, Smithsonian Astrophysical Observatory, Cambridge, Massachusetts 02138.